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Parallel-slab polarizing beam splitter and photopolarimeter

R. M.A. Azzam

University of New Orleans, razzam@uno.edu

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A dielectric-slab polarizing beam splitter (PBS) is described that generates two parallel beams of orthogonal p and s linear polarizations in reflection and functions as a diattenuator in transmission. The plane-parallel slab, which is set at Brewster's angle, is uncoated on one side and has an s-polarization antireflection coating (s-ARC) on the other side. Analytical results are presented for a PBS that uses a high-index slab coated with a low-index single-layer s-ARC, which is particularly suited for the IR. A novel multistage photopolarimeter that uses two such PBSs in series is described as being capable of sequential and simultaneous measurement of all four Stokes parameters of light. © 2007 Optical Society of America

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1. Introduction

Conventional polarizing beam splitters (PBSs) use crystal optics[1] or multilayer interference coatings[2] to divide an incident light beam into two (p and s) orthogonally linearly polarized beams that travel in different directions. In contrast with these one-to-two PBSs, a one-to-three, dielectric-slab BS is presented that produces two parallel beams of orthogonal p and s linear polarizations in reflection and a third beam in transmission. A multistage complete photopolarimeter that uses two such PBSs in a series is described for the sequential and simultaneous measurements of the first, second, and third normalized Stokes parameters of light using three pairs of detection channels. Previous designs of division-of-amplitude photopolarimeters are briefly reviewed elsewhere.[3]

2. Parallel-Slab Polarizing Beam Splitter

Figure 1 shows the PBS as a plane-parallel dielectric slab of thickness d_2 and refractive index n_2 whose front surface is uncoated and reflects incident light in air at the Brewster angle, $\phi_B = \arctan(n_2)$. Therefore the first reflected beam (beam 1) from the front surface of the slab is purely s polarized. The back surface has an antireflection coating for the s polarization (s-ARC) at the Brewster angle. Consequently, the light beam reflected from the backside of the slab is purely p polarized and is totally refracted as it exits the slab to air (beam 2) in a direction parallel to the first-reflected beam. There are no higher-order reflected beams. The only transmitted beam (beam 3) has both p- and s-polarized components that have experienced different attenuations in propagating through the slab.

From basic geometrical optics and the Brewster condition, the lateral separation D between the two parallel, orthogonally polarized, reflected beams is given by

$$D = 2d_2/n_2(n_2{}^2 + 1)^{1/2}. \tag{1}$$

The simplest s-ARC at the Brewster angle is a transparent single layer of refractive index n_1 and metric thickness d_1 given by

$$n_1 = \sqrt{2}n_2/(n_2{}^2 + 1)^{1/2}, \tag{2}$$

$$d_1 = 0.3536(\lambda/n_1), \tag{3}$$

where λ is the vacuum wavelength of light. The thin-film s-ARC specified by Eqs. (2) and (3) was first proposed in Ref. 4, and applied to selected areas on the *same* (front) side of a dielectric substrate to produce any desired two-dimensional spatial binary polarization patterns in reflected light. A reflected beam with periodic *temporal* binary polarization modulation (between the p and s states) is also obtained when the same coating (with thickness that alternates between 0 and d_1) is applied to the front surface of a synchronously rotating disk.[5] It is apparent that a multilayer s-ARC can be applied on the backside of the slab, but this is not considered here.

The author (razzam@uno.edu) is with the Department of Electrical Engineering, University of New Orleans, New Orleans, Louisiana 70148.

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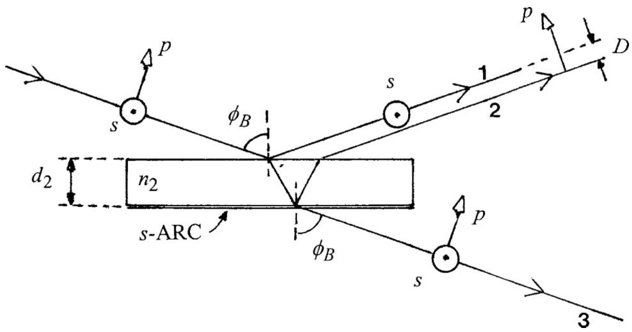

Fig. 1. Dielectric-slab PBS. A light beam incident on the slab at the Brewster angle ϕ_B is split into two reflected beams 1 and 2 that are purely s and p polarized, respectively, and a transmitted beam 3 that has both p- and s-polarized components. The front surface of the slab is uncoated and the back surface has an s-ARC. d_2 is the thickness of the slab, and D is the separation of the parallel reflected beams with orthogonal polarizations.

At the Brewster angle, the intensity reflectances of the front and back surfaces of the slab for s- and p-polarized light, respectively, are given by[4]

$$R_{\mathrm{fs}} = \cos^2(2\phi_B) = \left[(n_2^{\,2} - 1)/(n_2^{\,2} + 1)\right]^2, \tag{4}$$

$$R_{\mathrm{bp}} = [R_{\mathrm{fs}}/(2 - R_{\mathrm{fs}})]^2. \tag{5}$$

The corresponding intensity transmittances of the transparent slab for the p and s polarizations are given by

$$T_{\mathrm{p}} = 1 - R_{\mathrm{bp}}, \qquad T_{\mathrm{s}} = 1 - R_{\mathrm{fs}}. \tag{6}$$

The average reflectance of the slab for incident light with equal p and s components (i.e., light whose first Stokes parameter $s_1 = 0$) is given by

$$R_{\mathrm{av}} = (R_{\mathrm{fs}} + R_{\mathrm{bp}})/2. \tag{7}$$

From Eqs. (5) and (7), we obtain

$$R_{\mathrm{av}} = (R_{\mathrm{fs}}/2)\left(R_{\mathrm{fs}}^{\,2} - R_{\mathrm{fs}} + 4\right)/\left(R_{\mathrm{fs}}^{\,2} - 4R_{\mathrm{fs}} + 4\right). \tag{8}$$

For incident linearly polarized light of azimuth angle α from the plane of incidence (i.e., from the p direction), the two reflected beams have equal power when

$$\tan\alpha = (R_{\mathrm{bp}}/R_{\mathrm{fs}})^{1/2} = \left(n_2^{\,4} - 1\right)/\left(n_2^{\,4} + 6n_2^{\,2} + 1\right). \tag{9}$$

The overall reflectance of the slab under the condition given by Eq. (9) is

$$R = 2R_{\mathrm{fs}}R_{\mathrm{bp}}/(R_{\mathrm{fs}} + R_{\mathrm{bp}}),$$

$$R^{-1} = (1/2)\left(R_{\mathrm{fs}}^{\,-1} + R_{\mathrm{bp}}^{\,-1}\right). \tag{10}$$

As a specific example, for a Ge slab with refractive index $n_2 = 4$ in the IR, we obtain

$$\begin{aligned} \phi_B &= 75.964°, & D &= 0.1213d_2,\\ n_1 &= 1.372, & d_1 &= 0.2577\lambda,\\ R_{\mathrm{fs}} &= 77.855\%, & R_{\mathrm{bp}} &= 40.627\%,\\ R_{\mathrm{av}} &= 59.241\%, & R &= 53.392\%,\\ T_{\mathrm{s}} &= 22.145\%, & T_{\mathrm{p}} &= 59.373\%,\\ \alpha &= 35.844°. \end{aligned} \tag{11}$$

The film refractive index $n_1 = 1.372$ is close to that of ThF_4 (or BaF_2) at the IR wavelength $\lambda = 10.6$ μm.[6]

3. On Achieving a Given Average Reflectance Level

Suppose that we wish to have a PBS with a 50% average reflectance. Substitution of $R_{\mathrm{av}} = \frac{1}{2}$ in Eq. (8) gives the following cubic equation:

$$R_{\mathrm{fs}}^{\,3} - 4R_{\mathrm{fs}}^{\,2} + 8R_{\mathrm{fs}} - 4 = 0. \tag{12}$$

Equation (12) has one acceptable solution[7]:

$$R_{\mathrm{fs}} = 0.704402. \tag{13}$$

From Eq. (4), the required substrate refractive index is obtained:

$$n_2 = 3.383. \tag{14}$$

This index is very close to that of Si over a broad ($\lambda = 6$–12 μm) IR spectral range.[8] $n_2 = 3.383$ is also the refractive index of GaP at $\lambda = 0.580$ μm in the visible.[9]

For an average reflectance $R_{\mathrm{av}} = \frac{1}{3}$, a different cubic equation,

$$3R_{\mathrm{fs}}^{\,3} - 11R_{\mathrm{fs}}^{\,2} + 20R_{\mathrm{fs}} - 8 = 0, \tag{15}$$

is obtained that yields $R_{\mathrm{fs}} = 0.533990$ and $n_2 = 2.53534$. The latter refractive index is that of ZnS at the short wavelength end of the visible spectrum.[10]

4. Maximum Difference between R_{fs} and R_{bp}

It is interesting to consider the difference between R_{fs} and R_{bp}. For simplicity, R_{fs} is denoted by x. It follows from Eq. (5) that

$$\Delta R = R_{\mathrm{fs}} - R_{\mathrm{bp}} = \left(x^3 - 5x^2 + 4x\right)/(2 - x)^2. \tag{16}$$

Equation (16) shows that $\Delta R = 0$ in the limiting cases of $x = 0$ and $x = 1$, hence ΔR must reach a maximum at some value of x between 0 and 1. By setting the derivative of Eq. (16) equal to 0, we obtain yet another cubic equation,

$$x^3 - 6x^2 + 16x - 8 = 0. \tag{17}$$

Equation (17) has one acceptable solution,

$$x = R_{\text{fs}} = 0.635344. \tag{18}$$

The corresponding slab refractive index, calculated from Eq. (4), is

$$n_2 = 3.9844. \tag{19}$$

This index is essentially the same as that of Ge in the IR. The maximum reflectance difference is given by

$$\Delta R_{\max} = 0.373354. \tag{20}$$

5. Photopolarimeter Using Two Parallel-Slab Polarizing Beam Splitters

Whereas a conventional PBS splits an incoming light beam into two beams of orthogonal linear polarizations, the parallel-slab PBS shown in Fig. 1 does the same in reflection, *and* provides a third beam in transmission. This makes this PBS particularly suited for Stokes-parameter photopolarimetry.

Figure 2 shows a photopolarimeter that employs two parallel-slab PBSs (PBS1 and PBS2) with a 45° optical rotator (OR) in the middle. (Because of the diattenuation introduced by the slab in transmission, a rotation other than 45° may be optimum.) PBS1 generates reflected beams 1 and 2, and PBS2 produces reflected beams 3 and 4. The 45° optical rotator OR can be a quartz plate, whose optic axis is perpendicular to its faces and parallel to the beam, a twisted-nematic liquid-crystal cell, or a magneto-optic Faraday rotator. Alternatively, one can do without this OR by rotating the plane of incidence for light reflection at PBS2 by 45° with respect to the plane of incidence for light reflection at PBS1. By use of the Mueller calculus,[11] it can readily be shown that detection of light beams 1 and 2 can be dedicated (and calibrated) to determining the first normalized Stokes parameter s_1. Likewise, detection of light beams 3 and 4 can be dedicated to determining the second normalized Stokes parameter s_2.

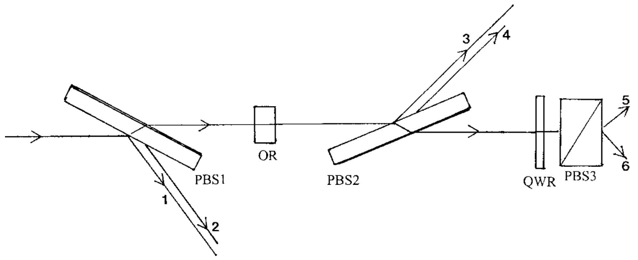

Fig. 2. Photopolarimeter that employs a cascade of two parallel-slab PBSs (PBS1 and PBS2) with a 45° optical rotator OR in the middle. PBS1 generates reflected beams 1 and 2, and PBS2 produces reflected beams 3 and 4. Detection of light in dual channels 1 and 2 and in dual channels 3 and 4 determines the first and second normalized Stokes parameters, respectively. The last stage, that consists of a quarter-wave retarder (QWR) followed by a conventional PBS (PBS3), produces beams 5 and 6, whose detection enables the determination of the third normalized Stokes parameter.

If the incoming light is totally polarized (which is often the case in ellipsometry[11]), the remaining third normalized Stokes parameter s_3 is obtained by

$$s_3 = \pm(1 - {s_1}^2 - {s_2}^2)^{1/2}. \tag{21}$$

Therefore operation of this photopolarimeter is similar to that of the widely used rotating-analyzer ellipsometer but with no moving parts.

To measure the third normalized Stokes parameter s_3 independently (which is essential if the input light is generally partially polarized), a third stage is added to the photopolarimeter as shown in Fig. 2. It consists of a quarter-wave retarder (QWR) followed by a conventional PBS PBS3. Detection of light beams 5 and 6 enables the measurement of s_3, given that s_1 and s_2 are already determined by the first two stages of the polarimeter. To the best of my knowledge, this is the only division-of-amplitude photopolarimeter in which the first, second, and third Stokes parameters are determined separately and simultaneously.

6. Summary

A novel parallel-slab polarizing beam splitter is described that splits an incoming light beam into two reflected beams of orthogonal *p* and *s* linear polarizations and a third transmitted beam that retains both the *p* and *s* components. A detailed analysis of the essential features of this design is presented. A novel photopolarimeter that consists of two such beam splitters in succession, plus a circular-polarization detector, is realized in which the first, second, and third normalized Stokes parameters of input light are measured separately and simultaneously by three dual channels of orthogonal polarizations.

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